ROBOTIC TESTBED FOR SIMULATING SPACECRAFT RELATIVE MOTION

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ABSTRACT

There has been growing interest within the United States space community to develop autonomous rendezvous and capture (ARC) capability on unmanned space vehicles. Such technology will enable the realization of several high-priority missions such as the autonomous replenishment of the International Space Station, and on-orbit refueling and maintenance of satellites. There is, however, an inherent high cost associated with the research, development, and testing of autonomous rendezvous and capture in a space environment. Consequently, a robotic platform that is capable of accurately simulating spacecraft dynamic motion will enable researchers to conduct their studies in a low cost environment in which they can afford to implement their control strategies without inhibitions. There are several on-going projects that use robotic platforms to simulate relative spacecraft motion in a plane. However, most of these platforms are highly sophisticated and complex making them cost prohibitive for many institutions.

This paper presents the development of a fairly inexpensive test facility that uses mobile robotic platforms to simulate relative planar motion for evaluating ARC control system logic and sensing strategies. The simulator consists of a simulation computer, two mobile robot platforms, and a vision system. The simulation computer computes the dynamic behavior of the space vehicles in the space environment. The robot platforms representing the space vehicles will move in accordance to the simulated space vehicle behavior. The mobile robotic platforms used in the simulator are based on the Palm Pilot Robot that was designed by the Carnegie Mellon Robotics Institute. The robotic platforms use three omnidirectional wheels in a triangular arrangement that can drive the platform in any direction with independent control of rotation, meaning it moves holonomically in the plane. The holonomic motion control distinguishes this robotic platform from most common mobile robots.

INTRODUCTION

The potential benefits from autonomous rendezvous and capture technology are enormous. There are already several space applications in the works that require autonomous rendezvous and capture capabilities to bring about complete functionality. In the near term, autonomous rendezvous and capture capabilities will allow the United States to automate its resupply of the International Space Shuttle. In the United States space program history, a standard and automated capability to rendezvous and dock spacecrafts has never been developed. Instead, in-flight rendezvous and docking has traditionally relied on crews onboard the spacecraft to complete the maneuvers[1][2]. It is prudent to rely less on astronauts to perform mundane tasks such as resupplying the International Space Shuttle and maximize the use of automated system. An extension of such a capability will be to develop an extended autonomous supply line between Mars and Earth, bringing back collected samples and providing needed supplies to sustain humans working on Mars. Also, an understanding of the autonomous rendezvous and capture system serves as a stepping-stone in the development of other technologies such as formation flying capabilities in space vehicles. Spacecraft fixed in formations can bring about more accurate data collection as required in space applications such as MAXIM Pathfinder [3] and Stellar Imager [4].

This project is concerned with the development of an inexpensive hardware-in-the-loop simulation that can be used to evaluate different control strategies. It will offer a distinct advantage over software-based simulation because real time sensing, data collecting and processing will be carried out during the testing of the control strategies. We will discuss how this relatively inexpensive robotic platform can be used to simulate spacecraft dynamic motion. In other words, the robotic platform will be an effective tool for researchers to conduct their studies in a low cost environment in which they can afford to implement their control strategies without inhibitions.

DEVELOPMENT OF SIMULATION PLATFORM

When designing the robotic platform, certain characteristics were decided upon to make the robotic platform simple and effective. Firstly, it was decided that a two-dimensional platform would be built. The limitation of such a platform is that it will only be able to investigate coplanar satellite motion. However, examining satellite motion on a planar level is a good foundation to build upon before moving on to investigating the principles of autonomous rendezvous and capture as a 6 degrees of freedom problem. Secondly, as shown in Figure 1, it was decided to define the target space vehicle instead of the center of the Earth as the center of reference frame so as to simulate the greatest range of relative spacecraft positions and orientations given the limits of the robotic platform workspace. This meant that we would be examining the relative position and velocity of the robotic platform acting as the chase space vehicle with respect to a fixed target acting as the target space vehicle, instead of relative positions and velocities of two space vehicles with respect to the Earth.

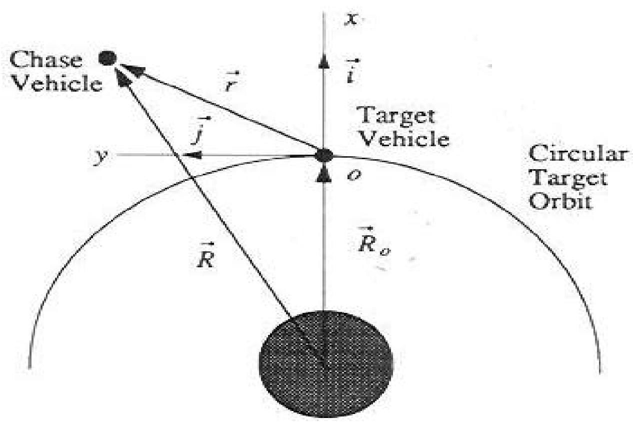

Figure 1. The Local Reference Frame [10]

The simulation platform consists of a robotic platform, a fixed target, a central processing unit, a computer vision system and wireless modems. The robotic platform chosen for the purpose of simulating orbital maneuvers is the Carnegie Mellon Palm Pilot Robot [6]. Certain modifications were made to the robot to satisfy our requirements. A Palm Pilot was not used along with the robot as all information processing was done at the central processing unit. It is possible to utilize Palm Pilot in our robotic platform so as to reduce the workload of the central processing unit and increase the speed of processing all the information. However, it is unnecessary in the case of only having one robotic platform, as the central processing unit is fully capable of processing all required information in a timely manner. If more robotic platforms are desired, it is a feasible option to transfer some of the workload to the Palm Pilots. A wireless modem, shown in Figure 2, was used in place of the Palm Pilot to allow the transfer of command inputs from the central processing unit to the Palm Pilot Robot.

Figure 2. Robot with wireless modem

The main chassis of the Palm Pilot Robot was kept intact. The main feature of the Palm Pilot Robot is its ability to perform holonomic maneuvers and consequently it is able to simulate the orbital maneuvers of a satellite. The driving force of the robot is provided by three hobby servo motors placed 120° apart from each other, as shown in Figure 3. The three servo motors are controlled by a Pontech SV203 controller board [7]. The controller board features a 5-channel, 8-bit analog-to-digital converter and can control up to eight servo motors. The servo motors are attached to omni-wheels, shown in Figure 4, which have rollers to allow the wheel to slide sideways.

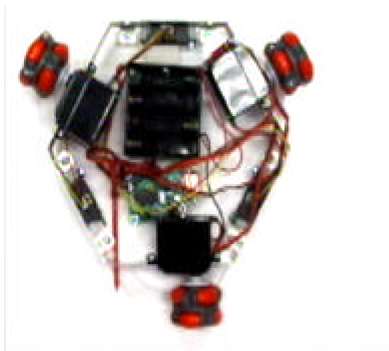

Figure 3. Bottom view of robot

Figure 4. Omni-wheel with rollers

As can be seen in Figure 5, the robot motion is controlled by rotating the individual wheels at different angular rates. The resultant wheel velocities produce both linear and angular motion of the robot platform.

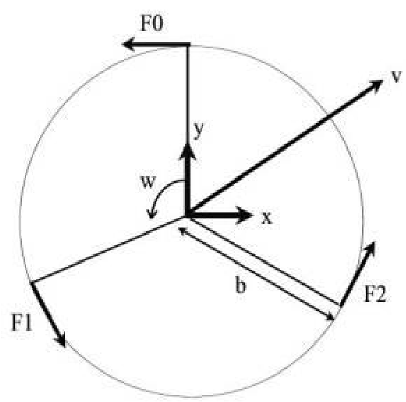

Figure 5. Velocity diagram of robot

A CMUcam [8] vision system, as shown in Figure 6, is used to provide continuous positional feedback of the robotic platform. In other words, the CMUcam plays a role similar to the Global Positioning System (GPS) in determining the position of satellites. The CMUcam is capable of tracking color at 16.7 frames per second at a baudrate of 115200 and has a maximum resolution of 80 x 143 pixels. The resolution is poor, but it is sufficient for the purpose of determining the centroid of the robotic platform. It is controlled by a microprocessor, which calculates the centroid of the robotic platform and the fixed target. The CMUcam is placed in a metal bracket mounted on a camera beam that is adjustable in height. The metal bracket keeps the CMUcam fixed in plane parallel to the smooth surface. The size of the workspace is determined by adjusting the height of the camera above the calibration plane. Given a fixed field of vision, increasing the height of the camera above the calibration plane increases the size of the workspace but decreases the resolution of the calibration plane based on a fixed resolution of the camera of 80 x 143. After determining the optimal size of the workspace, the conversation factor from calibration plane dimension to astrodynamic dimension is calculated.

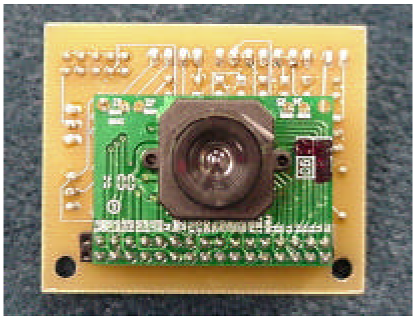

Figure 6. Front view of CMUcam

The simulation is controlled by a Pentium III 453 MHz standard desktop computer, which is interfaced with the computer vision system and the wireless modem via RS-232 serial communications. The software for the simulation is written entirely in Mathwork's Matlab environment. The basic program simulates the relative dynamic motion of the spacecraft in accordance with the Clohessy-Wiltshire linearized orbital equation of motion [9][10]:

$$\begin{aligned} \ddot{x} - 2n\dot{y} - 3n^2 x &= \frac{F_x}{m} \\ \ddot{y} + 2n\dot{x} &= \frac{F_y}{m} \end{aligned} \tag{1}$$

where

x, y	$\equiv$	local coordinates of chase vehicle
F_x, F_y	$\equiv$	external forces acting on chase vehicle
n	$\equiv$	orbital rate
m	$\equiv$	chase vehicle mass

We are only concerned with the in-plane motion (x and y dimension) of the Clohessy-Wiltshire linearized equations as our platform is only two-dimensional. The equations in (1) are the linearized orbital equations of the space vehicles when external forces are acting on the chase space vehicle. The control system will calculate the external forces required, F_x and F_y, to bring the chase space vehicle to a fixed relative position from the target space vehicle. Without any external forces acting on the chase vehicle, the chase vehicle will move around the target space vehicle based on astrodynamic forces. We had to decide on the orbital path that we wanted the chase space vehicle to have in order to best demonstrate relative motion of the two space vehicle. For this purpose, we chose an elliptical orbital path around the target space vehicle for the chase space vehicles. This is done by setting the initial x and y position and x and y velocities. Determining the optimal orbital path is done by simulation. Once the optimal orbital path has been determined, we can calculate the conversion factor from calibration plane dimension to astrodynamic dimension.

The challenge is how to maneuver the robot in order for the robot to move in an orbital path. Firstly, the orbital path will have to be scaled down from astrodynamic dimensions to the calibration plane dimensions. We use velocity as a variable to control the distance moved by the robot, given a constant time t_1 that the robot moves. Firstly, we chose a fixed time interval of points to simulate; we calculate the position of the chase space vehicle for every t_2 seconds. Therefore, there will be a time conversion of $t_2/(t_1+t_3)$ where t_3 is the processing time the control system take before a new command is given to the robot to move. This meant that an orbital path with a period of 24 hours could theoretically be converted with a simulated time period of 2 minutes. The purpose of such a time conversion is to allow the experiment to be conducted in a timely manner. By adjusting t_1 and t_2 within acceptable ranges, we can vary the simulated time period. However, t_1 cannot be so small that the robot will not be able to make any appreciable movement. Similarly, t_2 cannot be so big that the simulated orbital path no longer approximates the scaled down version of the orbital path. To determine the velocities of the robot at each point, we make use of the starting and ending point of each time interval. Given the starting and ending points, we can calculate the direction vector and magnitude of the velocity.

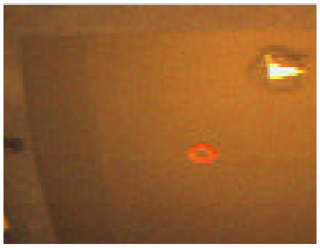

Fig 7. Captured image

Fig 8. Binarized image of chase vehicle

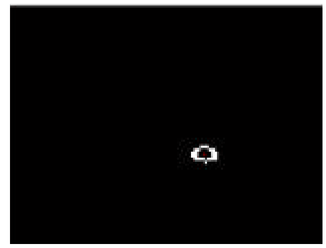

Fig 9. Binarized image of target

As shown in Figures 7 through 9, software was written for the CMUcam to determine the position of the target space vehicle and the chase space vehicle. A red circular coil represented the target space vehicle. A white triangle was placed on top of the Palm Pilot Robot, which is completely darkened to cover up any shiny surface or colored wires. The camera is tasked to track red color and determine the centroid of the red circular coil and then tasked to track the white color and determine the centroid of the white triangle. The centroid values are passed from the CMUcam to the central processing unit through serial communications. These centroid values represented the positions of the chase and target space vehicles in the image plane[11][12]. These centroid values are scaled into positions in astrodynamic dimensions.

Based on the position values of the chase space vehicle with respect to the target space vehicle, the Clohessy-Wiltshire equations will calculate the estimated position of the chase space vehicle at the end of the time interval. The rectifying force has to counteract the astrodynamic force and direct the chase space vehicle towards the target space vehicle. The rectifying force is calculated in terms of x, y, $\dot{x}$, and $\dot{y}$. The x position and y position are determined from the camera. However, the camera is not able to determine the $\dot{x}$ and $\dot{y}$ velocities of the chase space vehicle. Instead, we substitute these velocities with the theoretical $\dot{x}$ and $\dot{y}$ velocities derived from the Clohessy-Wiltshire equations.

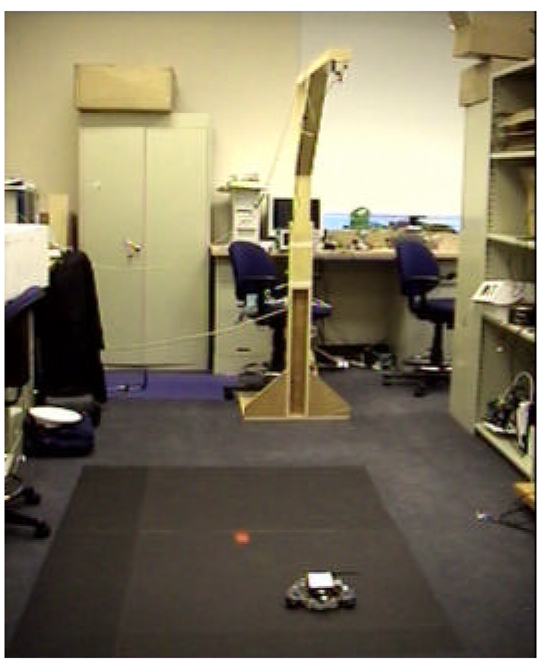

Figure 10. Picture of robotic testbed

Figure 10 shows a picture of the current robotic testbed configuration. In the picture you can see the Palm Pilot Robot (the chase vehicle), the red circle (the target vehicle), and the CMUcam mounted above the test area. At the writing of this paper the basic system architecture of the robotic testbed has been completed. Current work is focusing on verifying the robots motion with the Clohessy-Wiltshire equations. Future work will focus on adding ranging sensors to test control system logic and sensing strategies.

CONCLUSION

In this work, we have presented the basic concepts of developing a low cost test facility that uses mobile robotic platforms to simulate relative planar motion for evaluating spacecraft ARC control system logic and sensing strategies. The challenges involved have been identified and a simple ARC testbed has been described. The mobile robotic platforms used in the simulator are based on the Palm Pilot Robot that can move holonomically in a plane. The holonomic motion control distinguishes these robotic platforms from most common mobile robots. It is our hope that this research will provide a foundation for future efforts in the development and simulation of ARC and formation flying applications.

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